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Monitoring and modelling draining and resident soil water nitrate concentrations to estimate leaching losses

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ABSTRACT

Quantifying nitrogen (N) losses below the root zone is highly challenging due to uncertainties associated with estimating drainage fluxes and solute concentrations in the leachate. Active and passive soil water samplers provide solute concentrations but give limited information on water fluxes. Mechanistic models are used to estimate leaching, but require calibration with measured data to ensure their reliability. Data from a drainage lysimeter trial under irrigation in which soil profile nitrate (NO_3^-) concentrations were monitored using wetting front detectors (passive sampler) and ceramic suction cups (active sampler) were compared to NO_3^- concentrations in draining and resident soil water as simulated by the research version of the Soil Water Balance model (SWB-Sci). SWB-Sci is a daily time-step, cascading soil water and solute balance model that provides draining NO_3^- concentrations by accounting for incomplete solute mixing. As hypothesized, suction cup concentrations aligned closely with resident soil water concentrations, while wetting front detector concentrations aligned closely with draining soil water NO_3^- concentrations. These results demonstrate the power of combining monitoring and modelling to estimate NO_3^- leaching losses. Access to measured draining and resident NO_3^- concentrations, especially when complemented with modelled fluxes, can contribute greatly to achieving improved production and environmental objectives.

1. Introduction

Minimizing nitrogen (N) leaching losses from cropping systems requires a good understanding of the key physical, chemical and biological processes impacting on solute transformations and movement in soils. Predicting the movement of solutes through soil is far more challenging than predicting the soil water status (Flühler et al., 1996), and additional uncertainties due to the heterogeneous nature of soils (Addiscott, 1996) makes the quantification of N leaching losses even more difficult. Although physical monitoring provides direct estimates of solute concentrations in soil water, uncertainties regarding the pore volume being sampled and drainage fluxes make estimation of actual leaching losses subject to potentially large errors. Mechanistic modelling can be used to obtain concentrations as well as fluxes, but such models often require extensive calibration using measured data, and uncertainty remains regarding how well the key processes are represented in the model (Keating et al., 2001).

A range of devices has been developed over the years to sample soil water solutions, and are classified as either active or passive samplers, depending on whether action needs to be taken by the operator to obtain a sample (Litaor, 1988; Paramasivam et al., 1997). Active samplers, such as ceramic suction cups (SC), are commonly used worldwide. The wetting front detector (WFD) is a funnel shaped passive sampler which is buried in the soil and is able to alert a user when a wetting front (−2 to −3 kPa matric potential) has passed a specific depth in the soil by means of a visual indicator (Fig. 1) (see www.fullstop.com.au; Stirzaker, 2003, 2008). Following an irrigation/rainfall event, the funnel shape results in unsaturated flow lines converging towards a small cavity in its base where free water forms and can be sampled for chemical analysis. WFDs have been used successfully to improve understanding of the leaching of salts and NO_3^- in a system to which high rates of municipal sludge were applied (Tesfamariam et al., 2009).

Solute concentrations of soil water samples collected by active and passive samplers under similar conditions can differ markedly, and understanding the processes leading to these differences remains challenging (Haines et al., 1982). Passive samplers collect samples under relatively wet conditions, where solute concentrations are indicative of those in the water that is draining from one soil layer to the next. Active samplers provide solute concentra-

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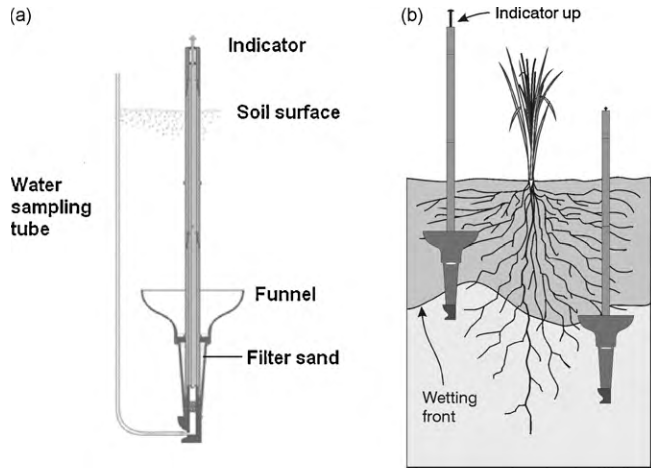

Fig. 1. (a) Schematic of the wetting front detector (WFD) passive sampler and (b) example of how WFD's can be strategically placed in the root zone to indicate when a wetting front has reached a specific depth enabling collection of a sample of the draining water.

tions indicative of those in the resident soil water, defined as all the soil water in a layer at a specific time. When sampling resident water the sample collected consists of the soil water held at suction less than the suction applied to the device (Magid and Christensen, 1993). Advantages and disadvantages in the in-field deployment of active and passive samplers have been extensively reviewed in the literature (Silkworth and Grigal, 1981; Barbee and Brown, 1986).

Water infiltrating through a soil profile is associated with a spectrum of pore-water velocities (Turner, 1958; Coats and Smith, 1964; Clothier et al., 1995; Ilsemann et al., 2002). Non-uniform solute movement has been observed as a result of faster flow through larger pores and slower flow in smaller pores (White, 1985). To account for this, models incorporate incomplete solute mixing algorithms to improve the description of solute movement in soil (Tillman et al., 1991; Corwin et al., 1991). The mobile phase of the resident water undergoes miscible displacement by incoming irrigation or rainfall water, while the immobile phase of the resident water is largely bypassed (Corwin et al., 1991).

SWB-Sci is a mechanistic, generic crop model which has undergone extensive testing regarding its ability to simulate crop growth and the soil water balance (Jovanovic and Annandale, 1999, 2000; Jovanovic et al., 1999, 2000; Annandale et al., 2000; Tesfamariam, 2004). Recently, N and P modelling subroutines have been incorporated into the model and tested using several datasets from *Zea mays* L. (maize) and *Triticum aestivum* L. (winter wheat) trials (Van der Laan, 2009). Soil water is simulated using a multi-layered cascading approach and crop growth is simulated by calculating a daily dry matter increment which is either radiation or water limited. Incomplete solute mixing is based on the approach developed by Corwin et al. (1991) in which a mobility coefficient was used to improve simulations of chloride movement in a soil column when compared to complete piston-type displacement. This approach is discussed in more detail later in the paper.

Crop N model testing exercises often compare measured and simulated values for aboveground crop N and inorganic soil N levels (Addiscott and Whitmore, 1987; De Willigen, 1991; Yang et al., 2000), but to the best of our knowledge, the approach developed by Corwin et al. (1991) or any similar approach has not been tested against measured NO_3^- concentrations from active and passive samplers. The hypothesis tested in this paper is that simulated resident soil water NO_3^- concentrations align with concentrations measured with SCs, while simulated draining soil water NO_3^- concentrations align with concentrations measured with WFDs. Approaches to and implications of using monitoring and modelling together to estimate NO_3^- leaching are discussed.

Table 1
Properties for the drainage lysimeter soil.

Soil property	Value
pH (H_2O)	4.73
Bulk density (kg m^{-3})	1120
Base saturation (%)	44.52
EC_e (dS m^{-1})	1.40
CEC (cmol(c+) kg^{-1})	4.418
C (%)	1.11
Sand (%)	72.3
Silt (%)	9.66
Clay (%)	18
Bray I P (mg kg^{-1})	11

2. Materials and methods

2.1. Drainage lysimeter trial

A drainage lysimeter with a volume of 6.1 m^3, a surface area of 4.7 m^2 and a depth of 1.3 m was used to represent a typical rootzone to study leaching losses at the local scale. The lysimeter was packed with sandy clay loam (18% clay) in mid-2006 and allowed to settle naturally for 17 months. The lysimeter is located at the University of Pretoria Experimental Farm (25°44′S 28°15′E, 1370 m above sea level). A gravel layer was placed at the conical base of the lysimeter to facilitate drainage. The following instrumentation was installed into the lysimeter: suction cups (SCs) (Sentek, Australia) at 15, 30, 45, 60, 80 and 100 cm depths; wetting front detectors (WFDs) at 15, 30, 45 and 60 cm depths; and ECH$_2$O-TE sensors (Decagon, Pullman, Washington) at 15, 30, 45, 60 and 80 cm depths (hereafter referred to as capacitance sensors). Data characterizing the initial soil properties were obtained by averaging results from samples collected at 0–15, 15–30, 30–45, 45–60, 60–80 and 80–100 cm depths (Table 1).

The vegetable test crop swiss chard (*Beta vulgaris* ssp. *cicla*) was used for this trial due to its ease of cultivation, relatively deep root system (∼80 cm) and because multiple harvests of the outer leaves can be made without having to re-sow the crop. Seedlings were transplanted into the lysimeter on 10 June 2008 (mid-winter) at an effective spacing of 20 cm × 30 cm. Harvesting was done by removing all leaves except the middle three from each plant. A representative 1 m^2 plot was harvested and dry mass determined by drying in an oven at 60 °C for 4–5 days. Leaf samples were analyzed for N content at each harvest, except for the final harvest when samples were lost, so an average N percentage for the three previous analyses was used for the final harvest value.

Suction was applied to the SCs using a 60 ml syringe immediately following irrigation/rainfall. According to the manufacturers, pulling the piston of the syringe back 2–3 times creates a suction of 60–70 kPa. If available, soil water samples were collected from both the WFDs and SCs the day following irrigation or rainfall. Drainage from the lysimeter was captured in large drums from which the quantity could be measured and a water sample taken for analysis. For each sample, NO_3^- was analyzed using an RQEasy Nitrate Reflectometer (Merck, Darmstadt, Germany).

Irrigation was applied with the primary objective of minimizing both plant water stress and N leaching. Following planting, small amounts of irrigation were applied at regular intervals. Thereafter, irrigation was applied to allow the WFD placed at 15 cm to respond, and as daily crop water demand increased, water was increased to allow the WFD placed at 30 cm to respond. Applications were made at weekly intervals, or more often if judged necessary to minimize plant stress. Nitrogen fertilizer (as calcium ammonium nitrate) was applied when average NO_3^- concentration from WFD samples fell